A USER'S GUIDE

TO

THE LUMINARY1A

LUNAR LANDING PROGRAMS

by

George W. Cherry

and

Donald Eyles

June 1969

Instrumentation Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

P63

Program 63, the Braking Phase, slows down the LM from about 5575 ft/s to less than 500 ft/s and guides the LM to hi-gate. The hi-gate targets are arranged relative to the lo-gate targets so that the P64 guidance program's nominal solution to the guidance problem between hi-gate and lo-gate tips the LM up and allows the astronaut to view the landing site.

The conditions at P63 ignition are nominally:

1,500,000 ft	horizontal range to the landing site
50,000 ft	altitude
near 0	altitude rate
5575 ft/s	velocity relative to the surface
106°	pitch angle

The actual P63 target state is never achieved because the P63 braking phase is terminated and the P64 visibility phase is started on the guidance pass after computed time-to-go, TGO, is less than the contents of TENDBRAK (62 seconds, presently). We must therefore distinguish between the P63 projected targets and the nominal hi-gate conditions. We define hi-gate to be where the switch from P63 to P64 is made (nominally at TGO = 60 seconds). The normal hi-gate conditions are:

23,000 ft	ground range to the landing site
7800 ft	altitude
-148 ft/s	altitude rate

460 ft/s	velocity relative to the surface
56^{o}	pitch angle

The actual P64 target conditions, projected about 60 seconds past hi-gate to avoid extreme guidance sensitivity as TGO approached zero, are actually near the surface of the moon.

From actual TIG in P63 until selection of P68 (the Confirm Lunar Landing Program) an Abort Discretes Monitor Routine monitors (at a frequency of 4 times/second) the input discretes from the ABORT and ABORT STAGE push-buttons. Thus the crew can automatically select P70 or P71, the DPS and APS abort programs, merely by pushing the appropriate abort button.

During P63 (and P64 and P65) the astronaut can display the PGNCS total guidance error on the FDAI error needles (ATTITUDE MON switch in PGNCS) by keying in V62 thru the DSKY. He can then steer out the PGNCS attitude errors with the AGS (GUID CONT in AGS and AGS MODE CONTROL in ATT HOLD) manually or with the PGNCS manually (GUID CONT in PGNCS and PGNCS MODE CONTROL in ATT HOLD) or automatically (PGNCS MODE CONTROL in AUTO).

Note, then, that there are three attitude control submodes in P63: AGS manual or PGNCS manual or PGNCS auto. This is also true for P64, and P65. (It is useful to be able to steer out the PGNCS guidance errors with the AGS ATT HOLD mode or the PGNCS ATT HOLD mode in order to assess the handling qualities of the analog autopilot and the PGNCS DAP. One word of caution, however; if the astronaut hits the ROD (rate -of-descent) switch while he is in PGNCS ATT HOLD, the LGC will irrevocably transfer him out of the auto guidance program modes into the ROD program mode, P66.

If the astronaut has the mode control switch in ATT HOLD and is not maintaining a small average attitude error, the hi-gate conditions will not be nominal because the explicit guidance equations are simply trying to reach the projected targets.

Prior to approximately 30,000 feet altitude the astronaut has X-axis over-ride in the AUTO mode. This simply means that he has yaw manual rate command/attitude hold capability during automatic pitch and roll control. At about 30,000 feet the LGC pre-empts the yaw-attitude control whenever the MODE CONTROL switch is in AUTO.

In major mode P63, P64,P65, or P66 the control of the throttle is automatic. Thus, the astronaut can assume the attitude control function with the AGS or PGNCS ATT HOLD modes in these major modes but he should let the LGC control the throttle. Indeed, Neil Armstrong has mentioned that this help from the LGC is very much appreciated and that simultaneous control of attitude (and horizontal velocity) and throttle (descent rate) is a formidable crew task.

When the throttle control switch is in auto the throttle output from the DECA to the engine is the sum of the voltage from the manual throttle and the voltage from the automatic throttle. (When in manual the auto-throttle contribution is ignored.) The manual throttle setting determines the minimum thrust obtainable. If the manual throttle commands a thrust above what the guidance equations desire, the guidance equations will compensate for the integrated excessive upward thrust by commanding the vehicle to point its thrust vector downwards. The manual throttle should be left at minimum throughout the landing, unless P67 is selected.

At 150 to 120 seconds TGO in P63 the guidance equations will ask for less than 57% thrust (number in erasable) and the throttle routine will command throttle-down. For a hot engine this will happen earlier, for a degraded engine later, and in fact the period under throttle control in the braking phase is there specifically to absorb small engine performance

variations. If the hardware does not obey the throttle-down command and sticks at maximum thrust, then about 40 seconds later the guidance equations will ask the vehicle to thrust downwards.

The displays for P63 are shown on the following pages.

P63 DISPLAY SEQUENCE

FLV06N61 R1 - TG R2 - TFI R3 - CROSS RANGE	(Indicates that Pre-burn Computations are complete)
FLV50N25 R1 - 00014	(Please perform IMU Fine Alignment. ENTER to bypass)
FLV50N18 R1 - ROLL R2 - PITCH R3 - YAW	(Please perform Auto Maneuver)
FLV50N25 R1 - 00500	(Only if LR is not in position #1)
FLV50N25 R1 - 00203	(Only if GUID CONT, THR CONT, and MODE CONTROL are not PGNS, AUTO, and AUTO respectively)

P63 DISPLAY SEQUENCE (Cont)

	PROGRAM ALARM Key in V05N09 FLV05N09 R1 - 1703	(Only if t = TIG - 50 seconds and state vector still not integrated to TIG - 30 seconds)
	V06N62 R1 - VI R2 - TFI R3 - DELTAVM	(Indicates that MIDTOAVE Routine has integrated state vectors to TIG - 30 secs for AVERAGEG)
Blank	V06N62 R1 - VI R2 - TFI R3 - DELTAVM	(Indicates that AVERAGEG will be started)
Return	V06N62 R1 - VI R2 - TFI R3 - DELTAVM	(Indicates AVERAGEG is on)

P63 DISPLAY SEQUENCE (Cont)

FLV99N62 R1 - VI R2 - TFI R3 - DELTAVM	(Indicates that TIG - 5 secs has arrived and requests astronaut to key PROCEED to permit engine ignition, R3 should show DELTAV due to ullage started at TIG - 7.5)
V06N63 R1 - VI R2 - H DOT R3 - H	(Indicates that TIG has arrived and astronaut has answered FLV99N62 with PROCEED. Indicates that DPS has been commanded on and aborts will be permitted.)
V97N63 R1 - VI R2 - H DOT R3 - H	(Only if the engine fails.)
V16N68 R1 - RANGE R2 - TG R3 - DELTAH	(TG, time-to-go, can be monitored for certain important events. DPS should be throttled down at about TG = XXBXX. Perhaps ground can assist in prediction. <u>Spacecraft can be commanded upside down if throttle sticks.</u> Major Mode should change to P64 and antenna should be commanded to Position #2 when TG = 01B00 approximately. R3 can be monitored for discrepancy between landing radar, measured altitude and LGC altitude. Key V57 to incorporate landing radar data and reduce discrepancy.

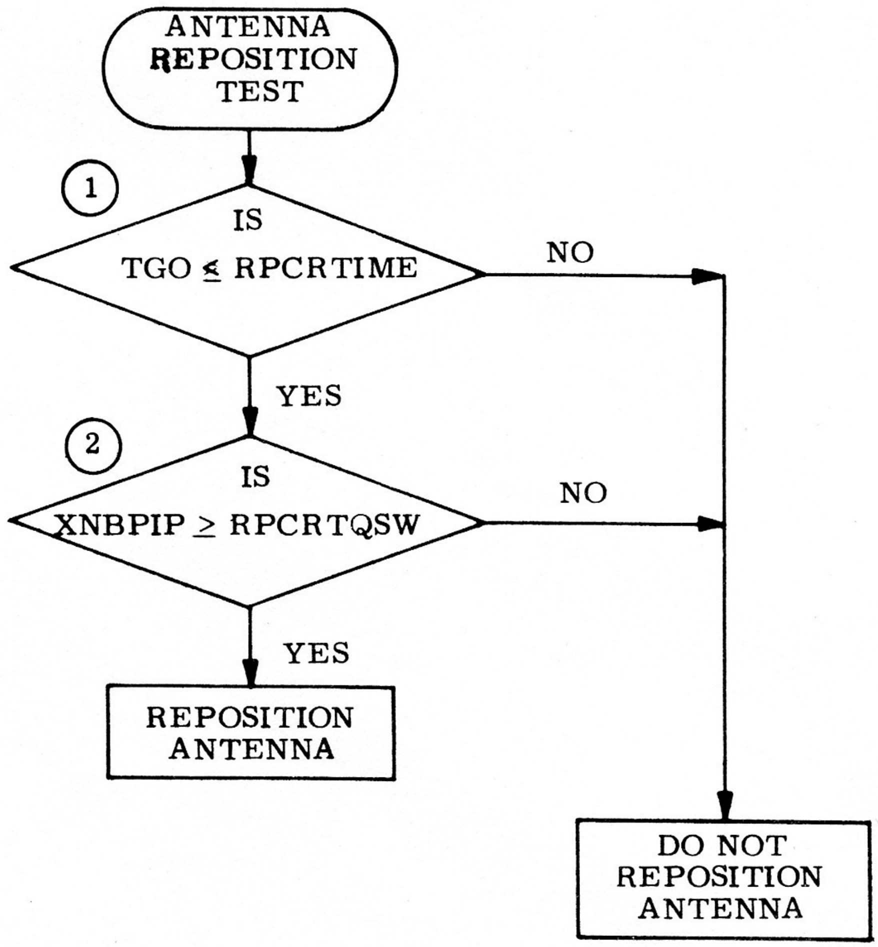
P64

When the LGC automatically selects P64, the antenna re-positioning routine begins to re-position the antenna from position 1 to position 2. The antenna re-positioning test routine (see Figure 1) makes the decision to re-position the antenna, but the pad-loads for this routine are so chosen that the antenna re-positioning is started at the same time as the change of major mode from 63 to 64. If the antenna does not reach position 2 within approximately 22 seconds after the re-position command is sent, a priority alarm is displayed (code 523).

The nominal initial conditions for P64, the Visibility or Approach phase, are of course the previously quoted hi-gate conditions. The actual P64 target state is never achieved because the P64 visibility phase is terminated and the P65 Automatic Terminal Descent phase is started on the guidance pass after computed TGO is less than the contents of TENDAPPR (12 seconds, presently). We define lo-gate as the time at which the major program mode is changed from P64 to P65 (TGO = about 10 seconds, nominally). The lo-gate conditions are, nominally:

60 ft	ground range to the landing site
145 ft	altitude
-3 ft/s	altitude rate
7 ft/s	horizontal velocity
6^{o}	pitch angle

The visibility phase begins with a pitch forward of about 10 degrees. When this maneuver is completed the commander can sight out his window to the site through the LPD reticle at the point indicated on the DSKY by the LPD angle, the right half of the split top line of noun 64. Yaw is controlled to keep the site in the plane of the reticle.



NOTE 1 For 1 to be satisfied, TGO must be less than or equal to the padloaded quantity RPCRTIME, presently 62 seconds.

NOTE 2 XNBPIP is the cosine of the angle between the LM + X-axis and the stable member + X axis. RPCRTQSW is the cosine of the pitch angle at which the second test should be passed. RPCRTQSW is currently loaded to be equivalent to + cos (180°).

ANTENNA RE-POSITIONING TEST ROUTINE

Figure 1

During most of the phase (after the astronaut has responded to the flashing DSKY request to enable the SITE REDESIGNATION routine until about 20 seconds before the end of the phase) the astronaut can use the ACA to redesignate the landing site. The PGNCS MODE CONTROL switch must be in AUTO for the ACA to function as a landing site re-designator. If this switch is in ATT HOLD, the ACA functions as a rate command/attitude-hold stick.

There is a peculiarity in the implementation of the site redesignation routine which requires some care in exercising the ACA to change the landing site. When the ACA is first moved out of detent, an input discrete to the LGC causes a computer interrupt. At the time of the computer interrupt a high-frequency monitor (once per fifty milliseconds) is set up to examine the input discretes from the break-out microswitches in the ACA and to check for return of the ACA to detent. At each sample, the monitor stores (buffers) the state of the channel which receives the input discretes from the break-out switches. The last sample taken from the input channel before the detection of the ACA return to detent is the one which is used to determine which direction to move the landing site. Two effects of this mechanization must be mentioned.

1. the landing site will not be moved until the stick is returned to detent.
2. if the astronaut lets the spring-loaded stick snap back so that it travels through detent and momentarily closes the microswitch on the opposite side of the detent position, the sampling of the switch discretes and the out-of-detent discrete could be such as to designate the landing site in the wrong direction.

Whenever the ACA returns to detent from the forward (- pitch) or backward direction, the site is moved farther or nearer the LM by $1/2^{\circ}$, as seen from the LM. Each left (- roll) or right (+ roll) movement of the stick is worth 2°.

The ATT HOLD sub-mode in P64 should prove very useful for it permits the astronaut to assess the handling qualities of the LM with the current status of the RCS jets (failed or unfailed) and the lower inertias encountered after the braking phase. In fact, after his final use of the ACA in conjunction with the LPD as a site redesignation device, the astronaut may switch from AUTO to ATT HOLD and control the attitude of the spacecraft manually while the LGC controls the throttle automatically with P64 and P65, until he wants a different descent rate from the automatic one and operates the ROD switch to select P66.

Incidentally, a good chance for the crew to assess the handling qualities of the LM is at the junction between P63 and P64 when the automatic guidance system commands about a (nominally) ten-degree thrust attitude-change (V62 must have been entered to see the total change at once). This maneuver, if done manually, gives the LM commander a chance to maneuver the spacecraft according to the FDAI error needles through a fairly large change.

The nominal velocity vector and range-to-go at 500 feet altitude are of particular interest because this altitude is often mentioned as the point at which the LM commander may exit the automatic landing programs and enter P66, the rate-of-descent program. The nominal conditions at 500 feet altitude are about:

1500 ft	ground range to the landing site
15.5 ft/s	altitude rate
57 ft/s	horizontal velocity
15^{o}	pitch angle
14^{o}	flight path angle
58 s	time to lo-gate
38 s	time remaining for redesignations

The crew has had about 100 seconds to redesignate the landing site when the 500-ft altitude point is reached.

The display for P64 is shown on the following page.

P64 DISPLAY SEQUENCE

MODE LIGHTS CHANGE TO 64	(Indicates that hi-gate has been reached and the new target conditions are lo-gate targets).
FLV05N09 R1 - 00523	(Possible priority alarm if antenna does not reach position 2 within about 22 seconds of beginning of P64. V32E should turn off R12 and all its alarms; but a non-priority alarm 511 can unfortunately occur repetitively after the V32E).
FLV06N64 R1 - TR/LPD R2 - H DOT R3 - H	(Requests astronaut to respond with PROCEED in order to set REDFLAG, the re-designate flag. ACA will re-designate landing site only if REDFLAG is set and MODE CONTROL is AUTO. REDFLAG is cleared when TR = 0. TR is the time remaining for landing site re-designation).

P65

Program 65, the Automatic Terminal Landing Phase major mode, has the guidance and control objectives of nulling the horizontal components of velocity, establishing a descent rate of about 3 ft/s, and achieving an erect orientation of the LM. The nominal initial conditions for this velocity-error nulling phase are the lo-gate conditions quoted previously.

To use Program 65 completely automatically the astronaut must leave both the MODE CONTROL switch and the THR CONTROL switch in AUTO. But, of course, he can fly the PGNCS FDAI error needles manually while P65 handles the throttle. This mode seems very useful if the astronaut does not have good visibility out of the window but can believe the landing radar and trust the PGNCS.

Notice that there is no positional control in P65. The spacecraft simply settles down from about 150-ft LGC altitude at about 3 ft/s while nulling the horizontal velocity at the beginning of P65 of about 7 ft/s. Because of this initial horizontal velocity the spacecraft nominally moves about 60 feet downrange between the beginning of P65 and touchdown.

The LGC automatic throttle which controls descent rate to 3 ft/s may be particularly useful if the LGC estimate of descent rate is reasonably accurate. The attitude control by the astronaut could be based on the PGNCS guidance errors displayed on the FDAI error needles or by a combination of eight-ball and out-the-window cues. Thus, P65 can be looked at as a P66 (with only one descent rate, 3 ft/s) and FDAI error-needle cues for nulling the horizontal velocity components and getting the spacecraft erect. This represents a somewhat over-simplification of the dynamical differences between P65 and P66, however. P66 has twice the DSKY display frequency and guidance-loop frequency that P65 has. Furthermore, the control-law time constants for nulling the descent-velocity error are quite

different in the two programs. The vertical thrust acceleration commanded once per two seconds in P65 is:

$$a_{t,\ vert} = (\dot{h}_D - \dot{h})\ /\ 10 + g \qquad \text{(P65)}$$

and the vertical acceleration commanded once per second in P66 is:

$$a_{t,\ vert} = (\dot{h}_D - \dot{h})\ /\ 1.5 + g \qquad \text{(P66)}$$

It can be seen that P66 will eliminate the descent error faster than P65. The reason for the longer time constant in P65 is that both the throttle command and the attitude commands are generated from the same equation in P65,

$$\underline{a}_{tc} = (\underline{v}_D - \underline{v}_{meas})\ /10 - \underline{g} \qquad \text{(P65)}$$

The thrust vector is commanded along $\underline{a}_{tc}$ and the throttle is set to make the thrust acceleration equal to the magnitude of $\underline{a}_{tc}$. The longer time constant is needed to stabilize the attitude commands which are generated from $\underline{a}_{tc}$. (Incidentally both the number 10 in P65 and the number 1.5 in P66 are erasable quantities. These values are our best present estimates of what these quantities should be.) The longer time constant in P65 is acceptable since the descent rate at the beginning of P65 is nominally about 3 ft/s (lo-gate) and there is very little descent rate error to null. Notice that there will be a difference in reaction of the two control laws to landing radar-noise. P66 will be more reactive.

While mentioning radar noise, it should be pointed out that P65, P66, and P67 all have the capability of establishing new landing-radar velocity-weighting factors. We are presently using 0.1.

We are doing fairly extensive testing of P65 in the completely automatic mode on our all-digital simulator. We will do some testing in the ATT HOLD mode on our hybrid. We hope that the crew will evaluate the usefulness and handling qualities of this mode. We believe that they ought to give it consideration because it only has one competitor, P66, for touchdown.

P66

Program 66, the rate-of-descent terminal phase major mode, requires manual attitude control but provides automatic control of descent rate by LGC control of the throttle. The astronaut can command changes in the descent rate by 1 ft/s incrementing or decrementing inputs from the rate-of-descent switch. (The 1 ft/s is actually a quantity in erasable storage.) This mode can be entered from P63, P64, or P65 by putting the MODE CONTROL switch in ATT HOLD and operating the ROD switch in one direction at least once. This mode is not designed for large velocities, or long ranges from the landing site and it is expected that it will be entered from P64 at about five-hundred feet altitude or later.

This appears to be the leading contender for the touch-down program and there has been a great deal of engineering and testing on this program. For example, in regard to engineering improvements, MIT/IL increased the frequency of the control loop to once per second, reduced the computation lag, improved the throttle compensation, and speeded up the DSKY displays. The LM pilot calls out the descent rate he reads on the DSKY to the LM commander. This display will now have a higher frequency and greater freshness.

P67

Program 67, the completely manual landing mode, does not appear to be very useful as a lunar landing touch-down mode but it may have other uses. Putting the THR CONT switch into manual selects P67. Mode should

at the same time be switched to ATT HOLD to enliven the ACA. Crew members have mentioned that it is a formidable task to land with manual throttle and manual attitude control. The throttle in particular appears to be hard to handle manually. We do not give this landing mode much emphasis at MIT/IL except to show that it works. There is no coding in P67 that is not also executed in P65 and P66, so the extensive testing of these modes largely verifies P67. We do not do man-in-the-loop type landings to any extent with P67. We do not anticipate that the crew will train on landing with P67.

The display for P65, P66, P67 is shown on the following page.

P65, P66, R67 DISPLAYS

V06N60	(Indicates that X-axis over-ride has been permitted in P65.)
R1 - V (HORIZ)	
R2 - H DOT	
R3 - H	

P68

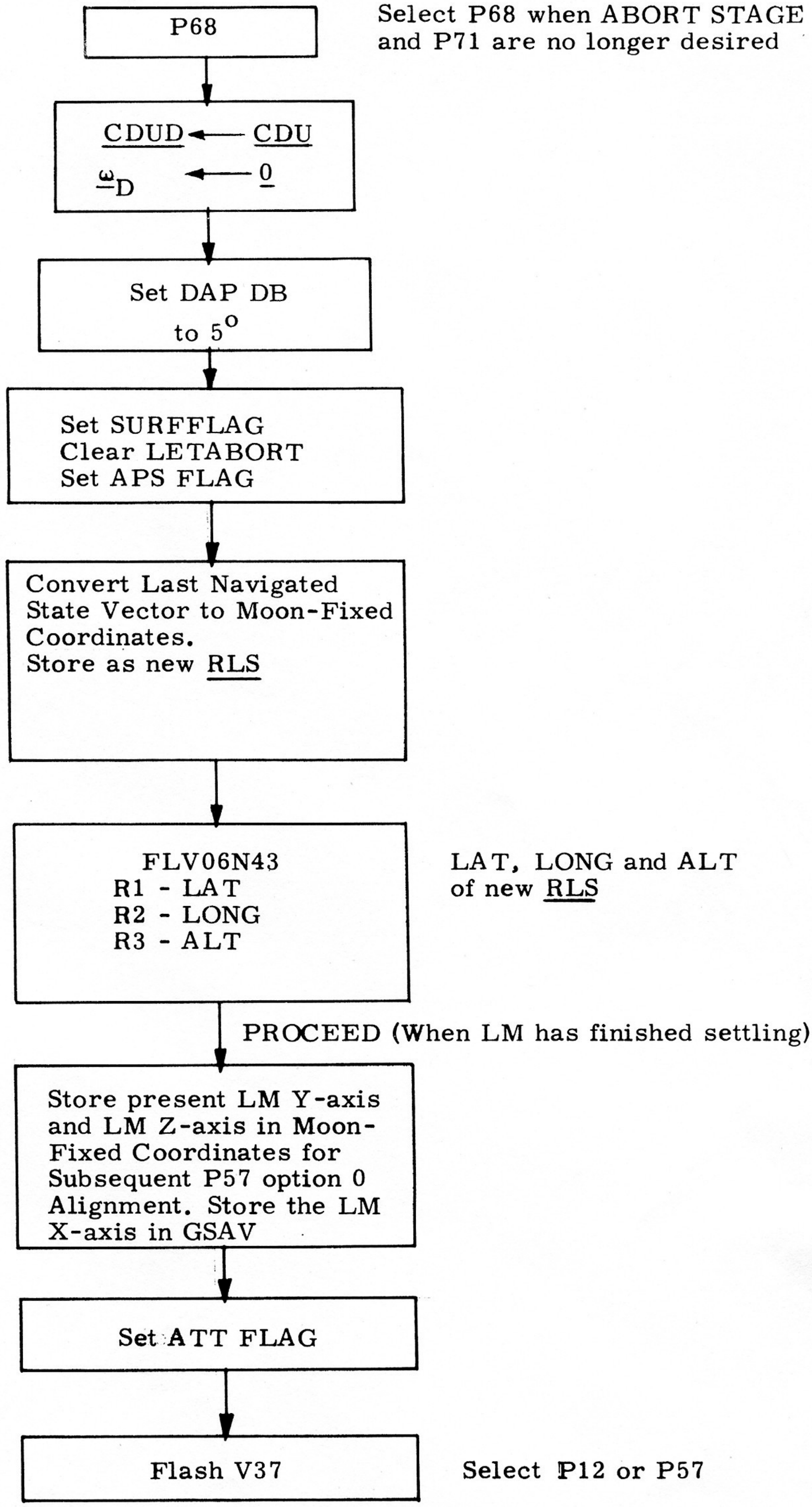
Program 68, the Landing Confirmation Program, is selected when the astronaut no longer wants the ABORT STAGE capability which he has in P65, P66, and P67. The program is simple enough to flow graph on one page: see Figure 2. The zeroing of the attitude errors and setting of the deadband to wide are done to prevent RCS jet firings for about 9 hours. However, every program change (V37E XXE) changes the deadband back to the crew's previously defined deadband. Also, the gyros can be torqued in P57 by 5° without astronaut notification. Therefore, it is desirable to turn off the DAP (MODE CONTROL to OFF) before calling P57, or key in V76E and keep the MODE CONT switch in ATT HOLD. If the latter procedure is used, the astronaut must key V77E and switch the MODE CONT switch back to AUTO before P12 ignition. Unless shifts in the attitude of the LM on the surface due to crew movement can be ruled out, again the DAP should be turned off.

The storage of the direction of the LM X-axis in GSAV is used for the calculation of the first display of N04 in P57. Noun 04 displays the "gravity error angle" defined as the angular difference between the present and the previously-defined gravity vector. The first time a gravity option alignment is used in P57, N04 will display the angle between the vector and the LM-X-AXIS because of the storage of the LM X-axis in GSAV in P68.

The SURFFLAG serves many purposes. It causes:

1. POO to stop integrating the LM state vector.

2. Routines which update the LM state vector (such as R21, R31, P21, etc.) to extrapolate the LM state vector by the Planetary Inertial Orientation Subroutine rather than KEPLER.



P68 OPERATIONS

Figure 2

3. Servicer to stop mass updating. (So that g will not be interpreted as thrust between TIG-30 and lift-off. This would incorrectly decrement the APS mass load.)

4. PIPA Compensation program to zero PIPA counters every 81.92 seconds to prevent overflow.

5. GYRO Compensation program to use g-sensitive compensation terms.